A preliminary investigation of biosecurity risks associated with biofouling on merchant vessels in New Zealand

ASHLEY D. M. COUTTS
MICHAEL D. TAYLOR
  Cawthron Institute
  Private Bag 2
  Nelson, New Zealand
  email: ashley.coutts@cawthron.org.nz

Abstract   Biofouling on international vessels is an important mechanism for the inadvertent transfer of non-indigenous marine species around the globe. This paper describes the nature and extent of biofouling on 30 merchant vessels (ranging from 1400 to 32 000 gross registered tonnes) based on analysis of hull inspection video footage collected by two New Zealand commercial diving companies. A new method for measuring biofouling communities is applied, which aims to incorporate the potential for various hull locations to house non-indigenous marine species. Our analysis revealed that out-of-service vessels and vessels plying trans-Tasman routes possessed greater levels of biofouling than more active vessels. Dry-docking support strips and sea-chest gratings generally had the highest levels of biofouling and may pose relatively high biosecurity risks. Any future biosecurity surveillance should target these hull locations for non-indigenous species.

Keywords   New Zealand; merchant vessels; hull locations; biofouling; non-indigenous marine species; management options

INTRODUCTION

The frequency at which non-indigenous marine species (NIMS) are being spread around the world appears to be dramatically increasing (Cohen & Carlton 1995; Ruiz et al. 1997; Hewitt et al. 1999; Ruiz et al. 2000). Ships are considered an exacerbator for this inadvertent transfer of NIMS (Carlton 1987; Nehring 2001; Minchin & Gollasch 2002). Shipping can disperse NIMS via a variety of mechanisms including ballast and bilge water discharges, biofouling or hull fouling (including de-fouling activities), sea-chests, sea-sieves, anchors, chain lockers, and piping (Schormann et al. 1990; Carlton et al. 1995). However, biofouling is beginning to be acknowledged, particularly in the Southern Hemisphere, as one of the most important mechanisms for the dispersal of NIMS (Cranfield et al. 1998; Thresher et al. 1999; Gollasch 2002; Hewitt 2002).

Although New Zealand does not presently have any regulations mandating the hygiene of vessel hulls, it does propose to develop a management regime for biofouling of visiting international vessels. In 2002, there were c. 3421 international vessel visits to New Zealand: 2581 merchant vessels, 794 pleasure craft, 34 passenger ships, and 12 barges/tugs (Biosecurity Council 2003). To successfully manage the biosecurity risks associated with biofouling on visiting international vessels, it is imperative to know which vessels and pathways pose the greatest biosecurity risks. However, it is not currently known which vessels, pathways, or levels of biofouling (e.g., species richness, diversity, biomass) constitute the greatest biosecurity risk.

Simplistically, the greatest biosecurity risk could be expected to be those visiting international vessels that possess the greatest levels of biofouling. For instance, slow-moving vessels (i.e., recreational, fishing, barges, oil exploration rigs, floating dry-docks, etc) typically spend prolonged periods of time stationary, thus are renowned for accumulating extensive biofouling over their entire hull, including NIMS that are capable of surviving slow voyages to new locations (e.g., Foster
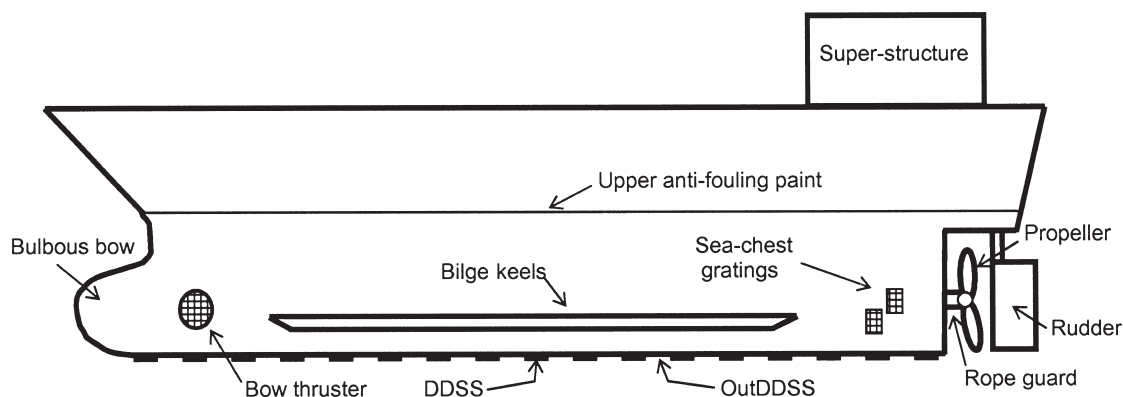
Fig. 1 Position of various hull locations sampled during this study. (DDSS, dry-docking support strips; OutDDSS, outside dry-docking support strips.)

& Willan 1979; Hay 1990; Hay & Dodgshun 1997; DeFelice 1999; Field 1999; Apte et al. 2000; Godwin & Eldredge 2001; Coutts 2002). However, their frequency of visits to foreign locations is typically fewer than the pattern of foreign voyages for faster-moving merchant vessels.

The biosecurity risks of frequently visiting merchant vessels may also be relatively high as high levels of biofouling, including NIMS, have been observed within anomaly areas of the hull (e.g., around the bilge keels, propellers, and rudders) as a result of variation in hydrodynamic flows and in the effectiveness of the anti-fouling paint (Rainer 1995; Coutts 1999; James & Hayden 2000; Schultz & Swain 2000; Lewis et al. 2003). Furthermore, such small pockets of biofouling may be provided with a greater window of opportunity to successfully reproduce and establish compared with the slower-moving vessels described above, owing to the relatively high number of ports frequented by merchant vessels (Minchin & Gollasch 2003).

Assessing the biosecurity risks of a given vessel is a complex task. It is not just the area of the hull that is covered by biofouling organisms or the total biomass of organisms as has been suggested (e.g., Rainer 1995). It might also be considered whether any NIMS are present, and other factors such as diversity (number of species present combined with a measure of their relative abundance).

This paper quantifies the nature and extent of biofouling within anomaly areas of the hulls of various merchant vessels operating in and visiting New Zealand. The potential of different areas of the hull to house biofouling is then used as a basis for interpreting biosecurity risk. The approach assumes that: (1) a greater diversity of fouling taxa (i.e., in terms of both taxa richness and relative abundance) equates to a higher likelihood of NIMS being present; and (2) more established biofouling communities constitute a greater biosecurity risk than undeveloped communities. The results have application for biosecurity managers in their need for efficient biofouling surveillance methods and for techniques to assess biosecurity risk at the border.

MATERIALS AND METHODS

Survey design

Underwater videos of the hulls of 30 merchant vessels (17 container vessels, 7 bulk carriers, 2 tankers, 2 roll-on/roll-off vessels, 1 supply vessel, and 1 passenger ferry) were randomly selected from libraries held by two New Zealand commercial diving companies (Divers Services Ltd and New Zealand Diving and Salvage Ltd). The vessels selected were either resident in New Zealand or visited New Zealand on a regular basis and ranged from 1400 to 32 000 gross registered tonnes. The vessels had been videoed between 1992 and 1999 using Panasonic Hydrovision (two-chip high-resolution) video cameras, immediately before in-water cleaning in Auckland, Tauranga, or Wellington. Information on vessel type was obtained from Maritime Data Services and the New Zealand Ship and Marine Society. Where possible, information on the maintenance history and voyage details of the vessels was obtained from records held by the diving companies. All vessels had been out of dry-dock for a minimum of 2 years.

Video footage targeted for quantitative sampling included areas of the hull (hull location) lacking anti-fouling paint (propeller), areas that often had damaged paint (bulbous bow), and areas containing ineffective anti-fouling paint (bilge keel, rudder, rope guard, and sea-chest gratings) (Fig. 1). Areas with inactive or old anti-fouling paint such as dry-docking support strips (DDSS; the positions under a vessel that cannot be painted with fresh anti-fouling during a dry-docking because of the position of docking blocks) were also included in this study. The area surrounding the DDSS (OutDDSS) on the bottom of vessels was also included for comparative purposes (Fig. 1). Quantitative sampling of the bow thrusters and sides of the hull was not possible owing to insufficient video footage of these areas.

Data collection

During viewing, the video was randomly paused 5 times within each of the eight hull locations on as many of the vessels as possible. The procedures employed by the divers operating the video cameras indicated that each quadrat corresponded to c. 0.45 × 0.45 m area of the hull. Taxa richness (number of biofouling taxa) and percentage cover data was derived using 50 random points marked on a 0.33 m television monitor.

Bare metal, anti-fouling paint, and 15 biofouling taxa (i.e., higher taxonomic groups) corresponding to four biofouling categories, as shown in Table 1, were used as a basis for describing the nature and extent of biofouling within and among the vessels. Only those hull locations described above were analysed, hence we did not consider levels of biofouling outside these locations such as along the waterline or the flat sides where certain taxa such as algae are more likely to be present (see: Coutts 1999).

The four biofouling categories correspond to a combination of the development (i.e., presence/

absence, succession, and growth) of biofouling generally observed on artificial structures (e.g., Marine Corrosion Sub-Committee 1944; Bishop et al. 1949; Pyefinch 1950; Woods Hole Oceanographic Institution 1952; Skerman 1960; Coutts 1999). Fine green and brown algae are classified as <5 mm in length whereas filamentous green and red algae are defined as >5 mm in length. Diatom and bacterial slimes could not be distinguished from bare metal and anti-fouling paint with any certainty and hence were not included in the study as separate taxa. Furthermore, owing to insufficient clarity of the video footage, no mobile biofouling organisms were observed and were therefore not included in the study.

The percentage cover data was also used to identify vessels and hull locations that contained a relatively high percentage cover of the higher taxonomic groups (i.e., biofouling categories C and D in Table 1). The percentage cover data for all taxa in categories C and D was weighted by one, whereas the percentage cover data for categories A and B was weighted by zero. This weighted percentage cover data was used as a simplistic basis for interpreting biosecurity risk under the assumptions described previously.

Statistical analyses

Patterns in the weighted percentage cover and richness data were investigated using general linear mixed models (GLMs), after a log(X+1) transformation of the data to satisfy normality and independence of error terms (PROC MIXED; SAS/STAT 1990). Vessels were grouped into three different vessel types (i.e., container vessels, bulk carriers, and other vessels). "Vessel type", "hull location", and the "vessel type" and "hull location" interaction term were analysed as fixed factors. "Vessel" was declared a random factor nested within "vessel type". "Vessel type" was grouped by the

Table 1 Biofouling taxa used in the study, categorised according to the general development of biofouling on artificial structures, as described in the literature (see text).

Biofouling category			
A	B	C	D
Bare metal	Fine green algae	Acorn barnacles	Solitary ascidians
Anti-fouling paint	Fine brown algae	Tubeworms	Compound ascidians
	Filamentous green algae	Coralline algae	Sea anemones
	Filamentous red algae	Bryozoans	Mussels
		Hydroids	Oysters
		Macroalgae	
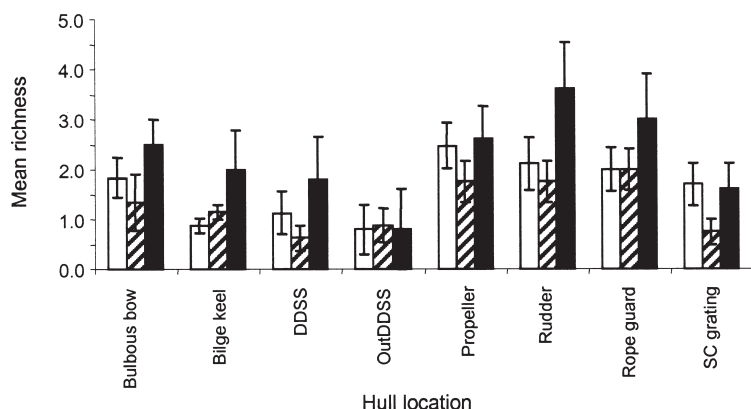
Fig. 2 Mean (±1 SE) richness within each hull location for the three vessel types used in the study. (DDSS, dry-docking support strips; OutDDSS, outside dry-docking support strips; SC grating, sea-chest gratings. Vessel type: □, container vessels; ▨, bulk carriers; ■, other vessels.)

"vessel type" and "hull location" interaction term after initial examination of both the richness and weighted percentage data revealed differences in the underlying variation for each combination of the interaction term. "Vessel" variability was investigated using the restricted maximum likelihood method (REML) and models of best fit were selected on the basis of the highest value of Akaike's information criterion (AIC). With a significant ($P < 0.05$) interaction term, each "vessel type" was analysed independently. Sources of variation in the final models were investigated using Tukey-Kramer pair-wise comparisons of means (SAS/STAT 1990).

The role of hull location in determining biofouling patterns was also investigated using multivariate analyses. Vessels were pooled and the data arcsine square root-transformed to stabilise variance. Then the mean percentage cover of each of the biofouling categories listed in Table 1 was determined for quadrats within each hull location. The Bray-Curtis measure (Bray & Curtis 1957) was then used to calculate dissimilarities among means and a visual assessment of the results provided by dendograms using the PRIMER program (Plymouth Routines In Multivariate Ecological Research; Clarke 1993).

RESULTS

Richness

Twelve of the 15 higher taxonomic groups listed in Table 1 were encountered during sampling (i.e., except for filamentous red algae, macroalgae, and sea anemones). The highest richness value was 11 taxa on a trans-Tasman container vessel (i.e., vessel 6; Table 2), eight of which were on the rudder. The final GLM for the richness data selected hull location

($P < 0.001$, d.f. = 7/215) and vessel type ($P < 0.001$, d.f. = 2/215). Pair-wise comparisons of means revealed significant differences ($P < 0.05$) between the OutDDSS and the bulbous bow, propeller, rudder, and rope guard, and between the DDSS and the propeller, rudder, and rope guard; OutDDSS had the lowest mean richness values overall, whereas propellers, rudders, and rope guards generally had higher values (Fig. 2). Significant differences were also found between the other vessels, and container vessels and bulk carriers; other vessels had higher mean richness values than the remaining vessel types for most hull locations (Table 2).
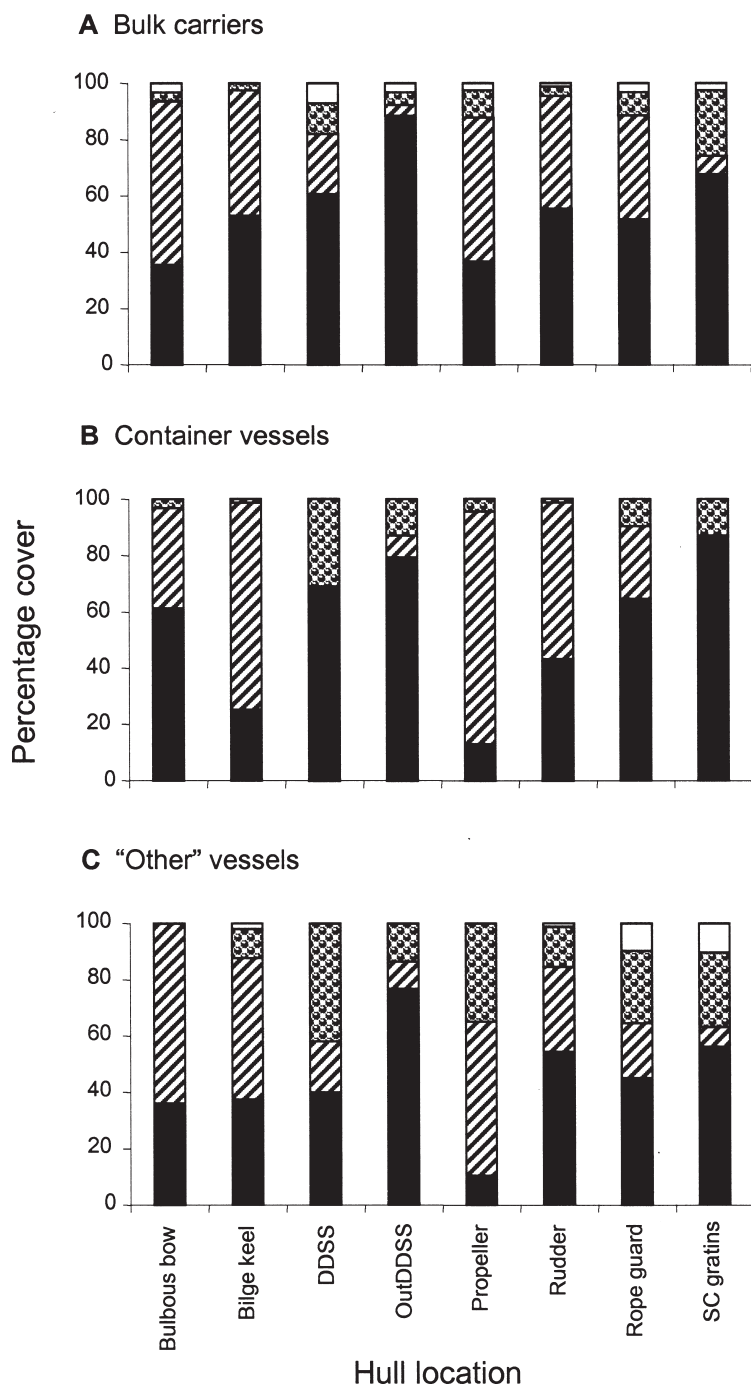
Percentage cover

An average of 54.1% of the quadrat areas surveyed were not visibly fouled (50.5% anti-fouling paint; 3.6% bare metal; Table 2). Biofouling category A (bare metal and anti-fouling paint) was noticeably most abundant for the OutDDSS strata amongst all three vessel types (Fig. 3; Table 3). Mean percentage cover of biofouling varied amongst hull locations (propellers > bulbous bows > bilge keels > rudders > rope guards > DDSS > sea-chest gratings > OutDDSS; Table 3). Biofouling category B taxa (i.e., fine and filamentous algae) were most dominant on propellers; a combination of both category A (antifouling paint) and B (algae) taxa were particularly dominant on bulbous bows, bilge keels, rudders, and rope guards (Fig. 3; Table 3).

Fine green and filamentous algae were relatively uncommon within DDSS, OutDDSS, and on seachest gratings. Rather, these locations had a greater percentage cover of category C taxa, acorn barnacles and tubeworms in particular (Fig. 3; Table 3). Category D taxa were most abundant within DDSS, but were also present on bulbous bows, rudders, rope

Table 2 Mean (±1 SE) percentage cover per quadrat of bare metal, anti-fouling (AF) paint, and 12 biofouling taxa for each of the 30 merchant vessels used in the study. Vessels have been sorted from least to greatest level of biofouling according to the presence of biofouling category (A<B<C<D). Vessel type: 1, container vessels; 2, bulk carriers; 3, other vessel types. Mean density of biofouling per vessel and taxa richness refer to taxa present upon each vessel (i.e., excluding bare metal and anti-fouling paint). Totals refer to mean (±1 SE) percentage covers for all vessels pooled.

Vessel	Vessel type	Mean density of biofouling per vessel	Taxa rich	Bare metal	AF paint	Brown surface algae	Green surface algae	Filament green algae	Acorn barnacles	Tubeworms	Coralline algae	Encrust bryozoans	Hydroids	Solitary ascidians	Compound ascidians	Mussels	Oysters
20	1	1.99±0.67	1	14.37±6.38	59.82±9.80	36.19±6.32	25.82±6.81										
19	1	2.81±0.64	2		63.47±6.38	15.82±5.34	0.34±0.34										
16	1	1.61±0.50	2	0.50±0.50	78.53±5.82	13.51±4.36	19.83±5.06	5.15±2.78									
8	1	3.02±0.61	3	12.50±5.30	45.76±6.71		9.18±3.98	5.96±2.87									
2	1	3.19±0.71	2	8.80±3.70	50.56±7.14		35.60±5.42	8.00±3.53	32.24±5.62								
3	1	3.60±0.66	3	12.50±5.30	40.71±5.25		16.80±4.00	18.90±4.01	3.18±1.64								
30	2	3.80±0.59	3	5.70±2.65	45.03±5.57	0.29±0.23	16.34±6.21	5.60±2.96	13.56±3.33								
17	2	2.96±0.74	4		61.40±7.69	15.90±5.44	17.47±5.52	6.59±3.02	0.29±0.23								
23	2	3.27±0.69	4		57.53±7.34	29.15±5.63	9.04±2.71	1.49±1.49	2.51±1.25								
11	2	3.15±0.61	4	3.49±1.72	56.67±6.57	23.85±5.15	10.55±2.89	6.30±2.83	1.31±0.57								
26	2	4.17±0.63	4	2.20±1.87	43.68±5.61	15.86±3.65	1.87±1.30	7.99±2.87	13.53±3.00								
27	2	2.06±0.42	4	3.87±2.26	69.33±5.95	18.65±4.24	9.38±3.90	4.55±2.39	1.08±0.55								
7	1	2.69±0.54	3	3.95±1.83	60.33±6.39	7.65±3.27	5.43±2.52		2.40±1.36	2.52±1.16							
18	2	0.83±0.24	4	7.07±3.17	82.08±5.52	21.24±4.89	5.70±3.24		2.89±1.30	2.50±1.21	4.29±1.62						
21	3	2.79±0.51	5		63.70±4.91	8.34±2.53	7.71±2.45	12.42±4.91	20.45±3.53	2.06±0.89	2.86±1.27						
29	3	3.44±0.64	5	4.15±1.91	50.36±5.97	30.97±6.42	5.83±2.52	8.05±3.00	1.14±0.71	0.63±0.39	4.46±2.21						
25	3	3.98±0.65	4		48.29±6.01	9.77±2.42		8.75±2.71	8.34±2.53								
12	3	4.33±0.80	5	2.86±1.45	39.38±6.24		11.49±3.70	6.26±2.14	21.80±5.73								
4	3	3.34±0.51	5	3.45±1.78	52.15±5.52	6.09±2.17	11.90±3.23	15.05±4.66	8.90±2.61		0.41±0.29						
28	3	2.37±0.41	6	1.40±.98	64.10±6.07	4.81±2.24	15.78±5.33	31.84±6.11	6.18±2.17	0.61±0.32	0.80±0.34						
15	3	3.42±0.64	5	1.75±1.26	53.59±6.18	5.85±2.52	12.67±3.89	0.40±0.40	7.34±2.24	19.60±5.98	0.70±0.70						
24	2	5.44±0.85	5	6.65±2.86	22.97±5.31	27.87±6.65	22.57±5.24	1.86±1.40	1.97±1.18			0.42±0.20					
13	2	4.09±0.78	5	9.94±4.48	36.83±6.41	5.10±2.47	23.10±4.33	11.28±4.17	2.65±1.41				2.20±1.06			0.36±0.36	
5	2	2.69±0.49	5	0.45±0.36	64.64±5.87		23.81±4.58	10.75±3.81	12.24±4.73		11.00±3.47		0.65±0.47			0.40±0.40	
10	3	4.54±0.73	6	3.47±1.61	37.55±4.97	4.44±1.89	35.20±6.21	7.57±3.71	1.30±0.72	3.52±1.02	1.98±1.26	0.65±0.28	15.97±2.37	2.19±0.69	18.59±2.64		
9	1	4.16±0.72	8	0.10±0.10	45.98±6.90		37.85±6.07	1.09±0.84	14.82±2.53		7.89±3.28				0.11±0.11	5.88±1.78	
22	3	6.67±0.78	9	2.50±1.78	11.01±2.32	8.51±2.72		5.26±2.30	19.09±2.70	9.40±2.29	3.89±1.64	5.71±1.54	8.52±1.87		12.56±2.38	10.69±3.04	0.35±0.24
14	3	4.76±0.53	7	0.53±0.37	37.87±5.22		13.03±3.05		0.77±0.40	10.46±1.80	0.51±0.51	8.27±1.73	24.29±3.34	9.76±2.34		1.19±0.91	0.23±0.16
6	3	4.22±0.54	11		45.59±5.37	2.57±1.55	1.66±0.81	4.63±2.11									
1	1	5.72±0.55		0.23±0.23	25.04±5.80												
Total	30	3.51±0.115	12	3.55±0.44	50.51±1.18	11.55±0.76	13.58±0.79	6.79±0.58	6.40±0.47	1.75±0.28	1.26±0.21	0.48±0.09	1.71±0.22	0.39±0.09	1.07±0.17	0.67±0.15	0.02±0.01

A Bulk carriers

B Container vessels

C "Other" vessels

Percentage cover

Hull location

Bulbous bow, Bilge keel, DDSS, OutDDSS, Propeller, Rudder, Rope guard, SC gratins

Fig. 3 Percentage covers of the four biofouling categories (see Table 1) within each hull location for the three vessel types used in the study. (DDSS, dry-docking support strips; OutDDSS, outside dry-docking support strips; SC grating, sea-chest gratings. Biofouling category: A, ■; B, ▨; C, ▨; D, □.)

guards, sea-chest gratings, and OutDDSS. However, category D taxa were largely confined to just four vessels (i.e., 6, 9, 14, and 22; Table 2). Vessels 6 and 9 were container vessels, which had spent several months out of service in Auckland Harbour immediately before in-water cleaning, whereas vessel 14 was a domestic tanker and vessel 22 a domestic supply vessel. With the exception of these

Table 3 Mean (±1 SE) percentage cover per quadrat of bare metal, anti-fouling paint, and biofouling taxa for each of the eight hull locations used in the study. Hull locations have been sorted according to the results of a cluster analyses (see Fig. 5). Taxa have been sorted according to biofouling category (A, B, C, and D). Mean % cover refers to biofouling taxa (i.e., biofouling categories B, C, and D only). (DDSS, dry-docking support strips; OutDDSS, outside dry-docking support strips.)

Biofouling category/ taxonomic group	Propeller	Bulbous bow	Bilge keel	Rudder	Rope guard	DDSS	Sea-chest grating	OutDDSS
A, Bare metal	25.67±2.55	0.09±0.09	0	0	0	0	0	0.53±0.53
Anti-fouling paint	0	43.93±3.41	43.40±3.22	52.06±2.70	53.46±2.65	58.33±3.50	70.03±2.48	83.26±2.55
B, Brown surface algae	35.08±3.12	6.24±1.63	7.06±1.79	14.87±2.04	12.48±1.80	8.73±2.42	3.45±0.87	1.50±0.78
Green surface algae	18.06±2.12	16.89±2.42	38.48±3.35	16.94±2.24	10.32±1.65	3.32±1.26	1.04±0.42	3.85±1.27
Filamentous green algae	5.38±1.45	28.47±3.20	6.76±1.77	9.61±1.67	7.49±1.58	2.56±1.13	0.41±0.32	0.78±0.49
C, Acorn barnacles	3.16±0.80	1.04±0.38	2.44±0.65	3.20±0.65	7.51±1.23	13.09±2.07	16.65±1.92	2.46±0.78
Tubeworms	0.81±0.34	0.38±0.30	0.39±0.18	0.78±0.23	0.39±0.21	5.80±1.69	0.88±0.38	4.54±1.20
Coralline algae	6.75±1.34	0	0	0.04±0.04	1.64±0.66	0.19±0.18	0.66±0.31	0.13±0.13
Encrusting bryozoans	0.49±0.33	0.06±0.06	0.25±0.14	0.23±0.11	0.65±0.30	1.01±0.40	0.35±0.17	0.69±0.26
Hydroids	2.06±0.70	1.23±0.67	0.37±0.17	0.80±0.28	2.10±0.62	3.01±0.84	3.14±0.89	0.83±0.30
D, Solitary ascidians	0.36±0.22	0	0	0.05±0.05	0.40±0.26	1.21±0.48	0.21±0.17	0.82±0.39
Compound ascidians	1.05±0.43	1.97±0.93	0	0.57±0.23	1.12±0.41	2.41±0.86	1.08±0.39	0.77±0.30
Mussels	0	0	0.30±0.17	0.36±0.16	2.38±0.72	0.06±0.06	1.99±0.77	0
Oysters	0	0	0.31±0.16	0.36±0.17	2.38±0.72	0.06±0.06	1.99±0.77	0
Mean % cover (taxa only)	5.64±0.41	4.33±0.41	4.31±0.40	3.65±0.30	3.58±0.28	3.18±0.22	2.30±0.22	1.25±0.17

vessels, category D taxa were limited to the bilge keel, rudder, rope guard, and sea-chest gratings on the other vessel type.

Multivariate analyses

Multivariate analyses separated three vessels (6, 9, and 22) from the remaining 27 surveyed as these vessels each had the greatest level of biofouling (richness and mean percentage cover) of the 30 vessels surveyed (Fig. 4; Table 2). Vessels 6 and 9 were the two out-of-service vessels, and vessel 22 was classified as a domestic supply vessel, all mentioned previously. Cluster analysis revealed three main groupings of hull locations, which are consistent with the patterns observed in the percentage cover data: (1) propeller; (2) bulbous bow, bilge keel, rudder, and rope guard; and (3) OutDDSS, DDSS, and sea-chest gratings (Fig. 5).
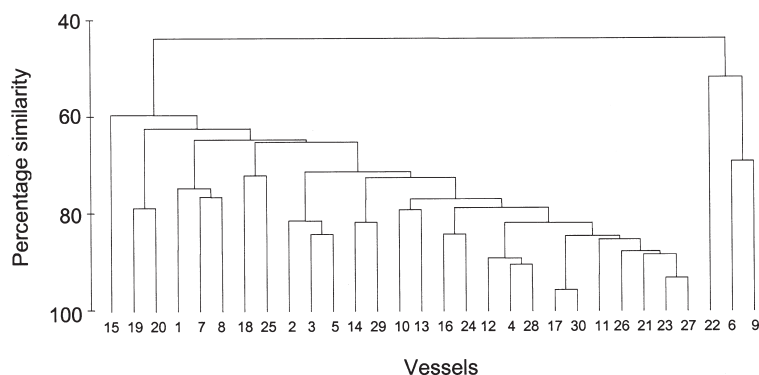
Weighted percentage cover

All three vessel types had a relatively high mean weighted percentage cover (i.e., category C and D taxa) within DDSS, as did the propeller, rope guard, and sea-chest gratings for the other vessel types (Fig. 6). The biofouling patterns within these hull locations for the other vessels contrasted with very little category C and D taxa within the bulbous bow location of these vessels. The final GLM for the weighted percentage cover data selected the vessel type and hull location interaction term ($P < 0.05$, d.f. = 14/198). Subsequent models for each vessel type resulted in marginally significant differences amongst hull locations for container vessels ($P = 0.051$, d.f. = 7/116), non-significant differences for bulk carriers ($P > 0.10$, d.f. = 7/47) and highly significant differences for the other vessels ($P < 0.001$, d.f. = 7/35). Pair-wise comparisons of means resulted in significant differences between the bilge keel and sea-chest gratings for container vessels, and between the bulbous bow and the DDSS, propeller, and rope guard for the other vessels.

## DISCUSSION

Richness and percentage cover

The archived video footage of underwater hull assessments proved to be a cost-effective way of quantifying levels of biofouling taxa at selected hull locations on a wide range of merchant vessels

Fig. 4 Dendogram showing the similarity in the mean percentage cover per quadrat of bare metal, anti-fouling paint, and the 12 biofouling taxa for each of the 30 merchant vessels used in this study. See Table 2 for supporting data.
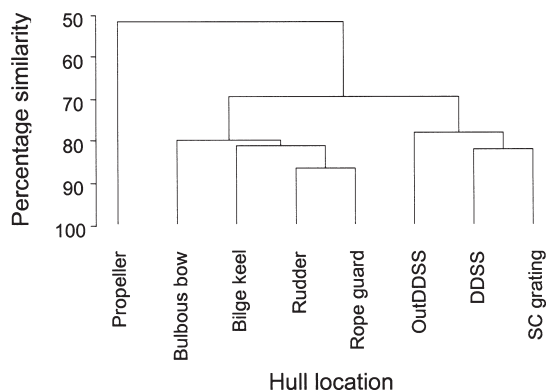
Fig. 5 Dendogram showing the similarity in the mean percentage cover per quadrat of bare metal, anti-fouling paint, and the 12 biofouling taxa for each hull location used in this study. See Table 3 for supporting data. (DDSS, dry-docking support strips; OutDDSS, outside dry-docking support strips; SC grating, sea-chest gratings.)
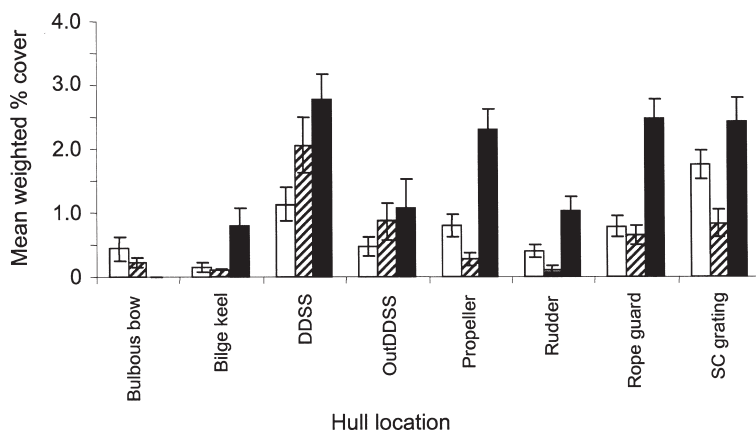
Fig. 6 Mean (±1 SE) weighted percentage cover within each hull location for the three vessel types used in the study. See materials and methods section for definitions of weighted percentage cover. (DDSS, dry-docking support strips; OutDDSS, outside dry-docking support strips; SC grating, sea-chest gratings. Vessel type: □, container vessels; ▨, bulk carriers; ■, other vessels.)

in New Zealand waters. It is important, however, to note that at the time of their video survey, the majority of the 30 vessels analysed probably had anti-fouling paint in excess of 36 months old given that these vessels were either requiring an in-water hull clean or a dry-docking extension. Therefore, considering that the effectiveness of modern-day anti-fouling paints at resisting biofouling declines

with age, the levels of biofouling encountered in this study were probably approaching worst-case biofouling scenarios typical of merchant vessels.

In light of the above, it was not surprising that all 30 vessels surveyed were fouled with at least one of the 15 taxonomic groups used in the study. Of the three vessel types, the six vessels classified as other were the most fouled, having the highest mean taxa

richness (per vessel), mean percentage cover, and mean weighted percentage cover of biofouling taxa. All six vessels classified as other traded either domestically throughout New Zealand or across the Tasman Sea (between Australia and New Zealand). Also, all vessels with category D taxa present were domestic or trans-Tasman vessels. Skerman (1960) and Coutts (1999) also found domestic and trans-Tasman vessels to be heavily fouled in relation to other vessel types surveyed. Generally this is because vessels plying similar latitudes with relatively short voyage durations are known to possess higher levels of biofouling than vessels that visit ports separated by vast latitudinal distances (Visscher 1928; Woods Hole Oceanographic Institution 1952; Coutts 1999; James & Hayden 2000; Lewis 2002; Lewis et al. 2003). Biofouling organisms are capable of surviving on vessels remaining at similar latitudes because of the relatively consistent ambient water temperatures (and sometimes salinity levels) at similar latitudes, and short voyages have little influence on the ability of biofouling organisms to feed and grow rapidly (Visscher 1928).

In contrast, many of the international container and bulk carrier vessels that had a relatively low mean taxa richness and percentage cover of biofouling organisms were often restricted to category B and C taxa. Such international vessels generally expose biofouling organisms to relatively long voyages at fast speeds (i.e., >18 knots), as well as relative extremes in temperature and salinity levels. Hence, only the more hydrodynamic-insensitive (e.g., cosmopolitan algae, acorn barnacles, tubeworms, and encrusting bryozoans) are able to survive on such relatively fast-moving vessels. For instance, Allen (1953) found that the cosmopolitan serpulid *Hydroides norvegica* (Gunnerus) and the bryozoan *Watersipora subtorquata* (d'Orbigny 1842) (as *W. cucullata* (Busk)) were the only surviving organisms on a 3-month voyage through tropical, warm temperate, and cool temperate waters on which the vessel's speed reached 30 knots.

Two container vessels had the highest levels of biofouling across hull locations out of all the vessels surveyed, with category B, C, and D taxa being present. Significantly, these were also trans-Tasman vessels and each had spent a minimum of three months laid-up in Auckland Harbour since their last dry-docking. Considering most merchant vessels currently utilise self-polishing copolymer (SPC) paints, which require water movement to expose a fresh surface from which the biocide is released, such extended inactivity results in insufficient biocide release to prevent biofouling and eventually enables a wide variety of biofouling communities to establish and mature. If operating conditions for a merchant vessel are optimal, SPC paints are capable of maintaining a vessel free from macroscopic biofouling for up to 5 years (Christie & Dalley 1987). However, despite the uniform areas of the hull being relatively clean, significant biofouling can still be present in relatively protected areas such as the gratings, surrounding intake pipes, bow thruster tunnels, rope guards, and/or in areas that lack anti-fouling paint (Coutts 1999; James & Hayden 2000; Wonham et al. 2000; this study). This is likely to be a consequence of: (1) turbulent water flow (such as over gratings and hull protrusions) causing rapid polishing and anti-fouling "polish-through"; or (2) low flow, as in static pockets, which would be similar to the situation with laid-up vessels. The net effect of both is inadequate biocide release to prevent biofouling.

Interestingly, SPC paints are known to foul with some species of diatom slimes, *Amphora* spp., and algal species such as *Enteromorpha*, *Ectocarpus*, and *Ulothrix* spp., which are resistant to the copper and triorgano-tin biocides in the paint (Christie et al. 1976; Hall et al. 1979; Evans 1981; Reed & Moffat 1983; Callow 1986). Diatom and other algal species may also be able to colonise protected areas of vessels more readily than the more exposed areas of the hull (Callow 1986). This is because protected areas of vessels (e.g., bow thrusters, rudder recesses, and gratings) are subject to turbulent flows, as opposed to the more laminar flows at more uniform areas of the hull (Schulz & Swain 2000). These differences in flow regimes may result in lower leaching rates of the toxic biocides in the protected areas, which may enable various algal species to colonise them. Given that the fouling process is often sequential, beginning with colonisation of the surface of the hull by bacteria followed by settlement of free-swimming algal spores and invertebrate larvae (e.g., Bishop et al. 1949; Woods Hole Oceanographic Institution 1952; Greene & Schoener 1982), early algal colonists and some invertebrates may provide a suitable non-toxic surface for a wide range of other fouling organisms to attach and survive. This is supported by the fact that the protected areas on a number of the vessels surveyed were found to have category D taxa present.

The hulls of merchant ships are usually coated with SPC paints that are designed to be most

effective for a given vessel's optimal speed and the amount of time they propose to spend in port. For instance, fast-moving vessels that spend minimal time in port are likely to adopt harder, slow polishing, anti-fouling paints whereas slow vessels are likely to adopt softer, faster-polishing paints. At present, it is common practice for the same type of paint to be applied to the entirety of a vessel's hull. However, some ships are now coated with different systems on different parts of the hull and this approach could be extended to better protect niche areas (John Lewis pers. comm.).

Multivariate analyses

Multivariate analysis revealed three main groups of hull locations: (1) propeller; (2) bulbous bow, bilge keel, rudder, and rope guard; and (3) OutDDSS, DDSS, and sea-chest gratings, according to similarities in the presence, absence, and abundance of bare metal, anti-fouling paint, and the 12 biofouling taxa encountered. We propose that variation in the patterns of biofouling between these hull locations can largely be explained by one or a combination of the following factors: (1) presence, absence, or effectiveness of anti-fouling paint; (2) availability of sunlight; and (3) exposure to hydrodynamic flow.

Propellers for instance, are a unique hull location because they usually do not possess anti-fouling paint, just a non-toxic brass surface. However, the challenge for biofouling organisms is not to just colonise such a structure, but to survive the harsh turbulent environment while the propeller is in motion. This might explain the dominance of hydrodynamic-insensitive taxa with a high percentage cover (i.e., brown and green surface algae, acorn barnacles, tubeworms, and coralline algae), particularly towards the centre of the propeller where hydrodynamic forces are much less than at the extremities of the blades.

Bulbous bows, bilge keels, rope guards, and rudders formed the second grouping, primarily because of the presence and similar abundance of three algal taxa (i.e., fine brown, fine green, and filamentous green algae). Not surprisingly, this is largely explained by such locations receiving a plentiful supply of sunlight. Although bilge keels are often at depth, the angle of the bilge keels to the hull is such that the upper facing surface receives more available light than the adjacent flat surfaces. Furthermore, invertebrates were also noted living on the edges and on the undersides of the keels. One of the problems with bilge keel edges and weld seams is that the application of sprayed anti-fouling paint

is often thinner on these areas, hence they are subjected to more turbulent flow and higher polishing rates making these surfaces susceptible to biofouling (Godwin & Eldredge 2001; John Lewis pers. comm.). Furthermore, the undersides of the bilge keels provide sheltered areas where polishing rates are slower, thus enabling various biofouling organisms to colonise and survive.

Interestingly, rope guards and rudders in particular also possessed a variety of invertebrate taxa. Similarly, although bulbous bows are probably subjected to some of the strongest hydrodynamic forces on merchant vessels, the anchor chains often remove the anti-fouling paint from this location, thus providing a non-toxic surface for biofouling organisms to colonise. Unfortunately, little can be done to prevent the removal of anti-fouling paint from bulbous bows by anchor chains. Anchor chains may also be responsible for de-fouling and introducing marine biofouling organisms. Usually only hydrodynamic-insensitive biofouling taxa that are morphologically suited are capable of surviving such harsh hydrodynamic environments (e.g., Koehl 1982; Denny 1988). Although some hydrodynamic-sensitive taxa (e.g., Category B and C taxa) can colonise bulbous bows on vessels that have experienced prolonged periods of inactivity (e.g., vessels 6 and 9), it is unlikely that they would survive in this location if the vessel returned to service.

The third grouping of hull locations (i.e., OutDDSS, DDSS, and sea-chest gratings) was grouped together because of their relatively low abundance of algal taxa and high percentage cover of anti-fouling paint. This is because these locations, especially OutDDSS and DDSS, receive very little light as a result of the shading effects of bilge keels, hence limiting algal growth. Similarly, sea-chest gratings are usually located at the turn of the bilge and underneath the vessels where light is limited. OutDDSS were the least fouled hull location on average because of limited light availability coupled with the effective release of biocides as a result of their exposure to relatively normal hydrodynamic water flows. However, OutDDSS of the two most heavily fouled vessels (i.e., 6 and 9) were colonised by a range of biofouling taxa. As mentioned previously, their inactivity resulted in inadequate biocide release to prevent biofouling. In a similar context, Preiser & Ticker (1985) found that DDSS provided a nucleus for invertebrates to migrate into surrounding areas (OutDDSS) as a result of the leaching rates of the anti-fouling paints declining with time.

Although DDSS may be subjected to relatively strong hydrodynamic forces, this location was often colonised by category C and D taxa, including a relatively high mean weighted percentage cover for all three vessel types. Such areas usually possess old and ineffective anti-fouling paint, providing invertebrates with a suitable non-toxic surface to colonise. Sometimes, given DDSS are located at depth (e.g., 5–12 m), they are not as frequently exposed to fresh water as upper regions of the hull (e.g., ports established in fresh-water dominated environments), which may also contribute to the prolonged survivorship of particular biofouling organisms within this location (Visscher 1928; Apte et al. 2000). Rainer (1995) and Coutts (1999) also found DDSS of merchant vessels to possess a greater degree of biofouling than most other hull locations. Interestingly, James & Hayden (2000) generally found greater levels of biofouling organisms within DDSS of recreational craft compared with this location on merchant vessels.

Weighted percentage cover

Variation in the weighted percentage cover data was shown to be dependent on vessel type with the other vessel category, which included the two trans-Tasman vessels, being particularly important. As stated previously, trans-Tasman vessels have been found to be more heavily fouled than vessels observed on most other pathways. DDSS, propeller, rope guard, sea-chest gratings, and rudder locations all had relatively high values for the other vessel type category, and DDSS had relatively high values for all three vessel types. DDSS and sea-chest gratings had the highest mean weighted percentage cover of the higher taxonomic groups (i.e., categories C and D), which suggests that these locations may have the greatest likelihood of housing NIMS. For instance, Coutts (1999) sampled the more uniform areas of merchant vessel hulls visiting Tasmanian waters, and found that DDSS had 89% of the taxa encountered (including NIMS). Furthermore, DDSS can represent 5% and 20% of the submerged area of the hull (Preiser & Ticker 1985), hence such areas are capable of housing high numbers of NIMS (Coutts 1999).

Biosecurity risk

The presence of certain taxa and relatively high levels of biofouling upon the hulls of merchant vessels does not necessarily equate to a significant biosecurity risk. The risk also depends on whether NIMS are present and their potential for establishment in the recipient location, whether or not the NIMS are already present there, and the extent of the potential negative (and positive) impacts (i.e., pest status). Clearly, the highest biosecurity risks of visiting international vessels visiting New Zealand are those carrying unwanted NIMS. The New Zealand Ministry of Fisheries has so far listed six unwanted NIMS (i.e., Mediterranean fanworm (*Sabella spallanzanii*), European green crab (*Carcinus maenas*), northern Pacific seastar (*Asterias amurensis*), Chinese mitten crab (*Eriocheir sinensis*), green seaweed (*Caulerpa taxifolia*), and the Asian clam (*Potamocorbula amurensis*) that have not yet been recorded in New Zealand waters. These pests present major ecological and economic threats if they were to become established (Mountfort 1998; Biosecurity Council 2003).

Of particular interest are the two heavily fouled trans-Tasman vessels that were laid up in Auckland for 3 months before the survey. Although trans-Tasman vessels are likely to have been responsible for introducing a wide variety of NIMS to New Zealand, to date these species have been relatively benign, hence their biosecurity risks appear to be negligible (Cranfield et al. 1998). If these vessels were put back into service, however, a key question is whether these well established fouling communities would be more or less susceptible to invasion from NIMS during their visit to Australia. For instance, the classic hypothesis proposed by Elton (1958), which states that species diversity enhances community resistance to invasion by exotic species, would suggest that the fouling communities on these vessels would be relatively immune to invasion by NIMS.

Alternatively, recent studies have shown that communities high in species diversity are more likely to be invaded by exotic species (e.g., Robinson et al. 1995; Planty-Tabacchi et al. 1996; Wiser et al. 1998; Levine & D'Antonio 1999; Lonsdale 1999; Stohlgren et al. 1999; Levine 2000). If this alternative hypothesis is accepted, then heavily fouled trans-Tasman vessels may be more susceptible to invasion by NIMS and therefore capable of introducing unwanted species (e.g., *S. spallenzanii*, *C. maenas*, and *A. amurensis*) to New Zealand.

Many measures such as dry biomass, species or taxa richness, species diversity, and percentage cover of biofouling organisms upon a vessel's hull have been used to assess both the performance of anti-fouling paints and to better understand biofouling processes (Visscher 1928; Pyefinch 1950; Woods

Hole Oceanographic Institution 1952; Cologer & Preiser 1981), and to identify vessels and hull locations that present biosecurity risks (Skerman 1960; Huang et al. 1979; Rainer 1995; Coutts 1999; James & Hayden 2000; Godwin & Eldredge 2001; Gollasch 2002; Minchin & Gollasch 2003; this study).

The weighted percentage cover variable used in this study provides an alternative approach as it aims to take into account not only the nature and extent of the biofouling, but also the development and growth of the biofouling community. However, the variable is clearly simplistic and somewhat biased in terms of the information it provides on biosecurity risk (e.g., it does not consider the presence of NIMS, or the biosecurity risks associated with certain taxa such as fine and filamentous algae, and mobile invertebrate species). We recommend that future research should be undertaken to further develop the approach. This should include a revision of the taxonomic groupings applied in this study. Also, the weighted percentage cover variable used in this study might be further refined by applying a weighting scale better suited to the invasion history of each taxa (e.g., the taxonomic groups used in this study could have been weighted by the number of unwanted NIMS from a list such as that described above).

Management

New Zealand is currently developing policy for addressing the biosecurity risks from hull and propeller cleaning and, in some states of Australia (i.e., Victoria), the risks are managed by prohibiting in-water cleaning of vessels over 200 gross tonnes (EPA 1999). Any future border surveillance of biofouling on merchant vessels should focus primarily on DDSS and sea-chest gratings, at least for sessile invertebrate species. It is also recommended that the inside of sea-chests be inspected for mobile organisms considering recent research has illustrated that such structures have the potential to disperse a variety of biofouling organisms (Richards 1990; Carlton et al. 1995; Dodgshun & Coutts 2002 see: http://www.cawthron.org.nz/Assets/seachest.pdf; Coutts et al. 2003). In addition, given that Coutts (1999) found microscopic alternate life stages of macrothalloid brown algae (which were fruiting in some samples) at the waterline of merchant vessels, this hull location should also be sampled for potential non-indigenous algal species (e.g., the invasive Japanese kelp *Undaria pinnatifida* is known to be translocated via the hulls of vessels; Hay 1990).

Despite DDSS being an inevitable consequence of the dry-docking procedure, they can be managed simply by the judicious placement of the docking blocks at each docking to ensure they are in a different location at alternative dockings. Alternatively, Preiser & Ticker (1985) devised a way of applying adhesive anti-fouling paint pads to the docking blocks before a vessel's docking, so that when the vessel departed the dry-dock these normally unprotected areas were treated with anti-fouling paint. However, as far as we are aware, this technology has not been pursued any further. Also, there are anti-fouling paints that can be applied under water, and these could be used to protect DDSS as well as damaged regions of the hull. Another, albeit expensive solution, might be to replace existing dry-docks with two sets of hydraulic docking blocks, so that anti-fouling paint can be applied to the entire bottom of the vessel using a two-stage operation.

A possible way of managing the biosecurity risks from propellers is to coat them with an anti-fouling paint resistant to cavitation, where the propeller motion provides the high flow necessary to dislodge any growth (John Lewis pers. comm.). It is significant to note that the most effective anti-fouling paint produced to date, tributyltin (TBT), will be phased out by 1 January 2008 (see: http://www.imo.org/home.asp?topic_id=161). This means that the application of anti-fouling paints that have been specially formulated for use on various types of vessels and hull locations is of paramount importance from a biosecurity perspective (Lewis 2002).

REFERENCES

Allen, F. E. 1953: Distribution of marine invertebrates by ships. *Australian Journal of Marine Freshwater Research 4(2)*: 307–316.

Apte, S.; Holland, B. S.; Godwin, L. S; Gardner, P. A. 2000: Jumping ship: a stepping stone event mediating transfer of non-indigenous species via a potentially unsuitable environment. *Biological Invasions 2*: 75–79.

Biosecurity Council 2003: Protect New Zealand: the biosecurity strategy for New Zealand. Wellington, Biosecurity Council. 63 p.

Bishop, M. W. H.; Pyefinch, K. A.; Spooner, M. F. 1949: The examination and interpretation of fouling samples from ships. *Journal of Iron and Steel Institute 161*: 35–40.

Bray, J. R.; Curtis, J. T. 1957: An ordination of the upland forest communities of Southern Wisconsin. *Ecological Monographs 27*: 325–349.

Carlton, J. T. 1987: Patterns of transoceanic marine biological invasions in the Pacific. *Bulletin of Marine Science 41*: 452–465.

Carlton, J. T.; Reid, D. M.; van Leeuwen, H. 1995: Shipping study: the role of shipping in the introduction of non-indigenous aquatic organisms to the coastal waters of the United States (other than the Great Lakes) and an analysis of control options. United States Coast Guard, Connecticut, Department of Transportation, Washington District of Columbia. Pp. 1–213.

Christie, A. O.; Daley, R. 1987: Barnacle fouling and its prevention. *Barnacle Biology*: 419–433.

Clark, K. R. 1993: Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology 18*: 117–143.

Cohen, A. N.; Carlton, J. T. 1995: Biological study. Nonindigenous aquatic species in a United States estuary: a case study of the biological invasions of the San Francisco Bay and Delta. United States Fish and Wildlife Service, Washington District of Columbia and the National Sea Grant College Program, Connecticut Sea Grant, NTIS No. PB96-166525.

Cologer, C. P.; Preiser, H. S. 1981. Fouling and paint behavior on naval surface ships after multiple underwater cleaning cycles. *In*: Costlow, J. D.; Tipper, R. C. *ed.* Proceedings of the Symposium on Marine Biodeterioration: an interdisciplinary study. Uniformed services. University of Health Sciences, 20–23 April 1981. Pp. 207–212.

Coutts, A. D. M. 1999: Hull fouling as a modern vector for marine biological invasions: investigation of merchant vessels visiting northern Tasmania. Unpublished MSc thesis, Australian Maritime College, Launceston, Australia. 283 p.

Coutts, A. D. M. 2002: A biosecurity investigation of a barge in the Marlborough Sounds. *Cawthron Report No. 744*. 59 p.

Coutts, A. D. M.; Moore, K. M.; Hewitt, C. L. 2003: Ships' sea-chests: an overlooked transfer mechanism for non-indigenous marine species. *Marine Pollution Bulletin 46(11)*: 1510–1512.

Cranfield, H. J.; Gordon, D. J.; Willan, R. C.; Marshall, B. C.; Battershill, C. N.; Francis, M. P.; Nelson, W. A.; Glasby, C. J.; Read, G. B. 1998: Adventive marine species in New Zealand. *NIWA Technical Report No. 34*. 48 p.

DeFelice, R. C. 1999: Fouling marine invertebrates on the floating dry dock *USS Machinist* in Pearl Harbour to its move to Apra Harbour, Guam. Hawaii Biological Survey, Bernice P. Bishop Museum Honolulu, Hawaii. Contribution No. 1999–013 to the Hawaii Biological Survey.

Denny, M. W. 1988: Biology and the mechanics of wave-swept environments. New Jersey, Unites States, Princeton University Press. Pp. 1–132.

Elton, C. S. 1958: The ecology of invasions by animals and plants. London, Methuen & Co Ltd. Pp. 1–181.

EPA 1999: Protecting the Victorian marine environment from marine pests: draft industrial waste management policy (ships ballast water and hull cleaning) and draft policy impact assessment. *Publication 673*. Southbank, Victoria. Environment Protection Authority. 95 p.

Field, D. 1999: Disaster averted? Black striped mussel outbreak in northern Australia. *Fish Farming International 26*: 30–31.

Foster, B. A.; Willan, R. C. 1979: Foreign barnacles transported to New Zealand on an oil platform. *New Zealand Journal of Marine and Freshwater Research 13*: 143–149.

Godwin, L. S.; Eldredge, L. G. 2001: South Oahu Marine Invasions Shipping Study (SOMISS). *Technical Report No. 20*. Honolulu, Hawaii Biological Survey, Bishop Museum. 104 p

Gollasch, S. 2002: The importance of ship hull fouling as a vector of species introductions into the North Sea. *Biofouling 18(2)*: 105–121.

Hay, C. H. 1990: The dispersal of *Undaria pinnatifida* by coastal shipping in New Zealand, and implications for further dispersal of *Undaria* to France. *British Phycological Journal 25*: 301–313.

Hay, C. H.; Dodgshun, T. 1997: Ecosystem transplant? The case of the *Yefim Gorbenko*. *Seafood New Zealand, May 1997*: 13–14.

Hewitt, C. L. 2002: The distribution and biodiversity of tropical Australian marine bioinvasions. *Pacific Science 56(2)*: 213–222.

Hewitt, C. L.; Campbell, M. L.; Thresher, R. E.; Martin R. B. 1999: Marine biological invasions of Port Phillip Bay, Victoria. *Technical Report No. 20*. Hobart, Australia, CSIRO Marine Research, Centre for Research on Introduced Marine Pests. 344 p.

Huang, X. M.; Ni, W. Z.; Lu, H. Q.; Lui, K. D. 1979: A study of the interrelation between service condition of ships and fouling organisms. *Oceanologia et Limnologia Sinica 10*: 82–90.

James, P.; Hayden, B. 2000: The potential for the introduction of exotic species by vessel hull fouling: a preliminary study. *NIWA Technical Report No. 16*. 15 p.

Koehl, M. A. R. 1982: The interaction of moving water and sessile organisms. *Science America 247*: 124–134.

Levine, J. M. 2000: Species diversity and biological invasions: relating local processes to community pattern. *Science 288*: 852–854.

Levine, J. M.; D'Antonio, C. M. 1999: Elton revisited: a review of evidence linking diversity and invasibility. *Okos 87*: 15–26.

Lewis, J. 2002: Hull fouling as a vector for the translocation of marine organisms. Phase I Study. *Ballast Water Research Series, Report 14*. Canberra, Australian Government Department of Agriculture, Fisheries and Forestry. 142 p.

Lewis, P. N.; Hewitt, C. L.; Riddle, M.; McMinn, A. 2003: Marine introductions in the Southern Ocean: an unrecognised hazard to biodiversity. *Marine Pollution Bulletin 46*: 213–223.

Lonsdale, W. M. 1999: Concepts and synthesis: global patterns of plant invasions, and the concept of invasibility. *Ecology 80*: 1522–1536.

Marine Corrosion Sub-Committee 1944: Fouling of ships' bottoms: identification of marine growths. *Journal of Iron and Steel Institute 150(2)*: 143–156.

Minchin, D.; Gollasch, S. 2002: Vectors—how exotics get around. *In*: Leppakoski, E.; Gollasch, S.; Olenin, S. *ed*. Invasive aquatic species of Europe: distribution, impact and management. London, Kluwer. Pp. 183–192.

Minchin, D.; Gollasch, S. 2003: Fouling and ships' hulls: how changing circumstances and spawning events may result in the spread of exotic species. *Biofouling 19*: 111–122.

Mountfort, D. O. 1998: Current status of ballast water treatment research at Cawthron Institute, Nelson, New Zealand. (Report prepared for Australian Quarantine and Inspection Services [AQIS], Canberra, Australia.) *Cawthron Report No. 446*.

Nehring, S. 2001: After the TBT era: alternative anti-fouling paints and their ecological risks. *Senckenbergiana Maritime 3(2)*: 341–351.

Planty-Tabacchi, A.; Tabacchi, E.; Naiman, R. J.; De-Ferrari, C.; Decamps, H. 1996: Invasibility of species-rich communities in riparian zones. *Conservation Biology 10*: 598–607.

Preiser, H. S.; Ticker. A. 1985: A novel system for preserving hull areas obscured by docking blocks for optimum fuel savings. United States Department of the Navy Report. Pp. 297–313.

Pyefinch, K. A. 1950: Notes on the ecology of ship-fouling organisms. *Journal of Animal Ecology 19(1)*: 29–35.

Rainer, S. 1995: Potential for the introduction and translocation of exotic species by hull fouling: a preliminary assessment. *Technical Report No. 1*. Hobart, Tasmania. Centre for Research on Introduced Marine Pests. 18 p.

Richards, A. 1990: Murricids: a hazard to navigation? Hawaiian Malacological Society. *Hawaii Shell News 38*: 10.

Robinson, G. R.; Quinn, F. J.; Stanton, M. L. 1995: Invasion of experimental habitat islands in a California winter annual grassland. *Ecology 76*: 786–794.

Ruiz, G. M.; Carlton, J. T.; Grosholz, E. D.; Hines, A. H. 1997: Global invasions of marine and estuarine habitats by non-indigenous species: mechanisms, extent, and consequences. *American Zoologist 37*: 621–632.

Ruiz, G. M.; Fofonoff, P. W.; Carlton, J. T.; Wonham, M. J.; Hines, A. H. 2000: Invasion of coastal marine communities in North America: apparent patterns, processes, and biases. *Annual Reviews in Ecology and Systematics 31*: 481–531.

SAS/STAT 1990. Version 6.11. Cary, North Carolina, United States, SAS Institute Inc.

Schormann, J.; Carlton, J. T.; Dochoda, M. R. 1990: The ship as a vector in biotic invasions. *Marine Technology and the Environment 19*: 147–152.

Schultz, M.; Swain, G. W. 2000: The influence of biofilms on skin friction drag. *Biofouling 15(1–3)*: 129–139.

Skerman, T. M. 1960: Ship-fouling in New Zealand waters: a survey of marine fouling organisms from vessels of the coastal and overseas trades. *New Zealand Journal of Science 3*: 620–48.

Stohlgren, T. J.; Binkley, D.; Chong, G. W.; Kalkhan, M. A.; Schell, L. D.; Bull, K. A.; Otsuki, Y.; Newman, G.; Bashkin, M.; Son, Y. 1999: Exotic plant species invade hot spots of native plant diversity. *Ecological Monographs 69*: 25–46.

Thresher, R. E. 1999: Diversity, impacts and options for managing invasive marine species in Australian waters. *Journal of Environmental Management 6*: 137–148.

Thresher, R. E.; Hewitt, C. L.; Campbell, M. L. 1999: Synthesis: introduced and cryptogenic species in Port Phillip Bay. *In*: Hewitt, C. L.; Campbell, M. L.; Thresher, R. E; Martin, R. B. *ed*. Marine biological invasions of Port Phillip Bay, Victoria. Centre for Research on Introduced Marine Pests. *Technical Report No. 20*. Pp. 283–295.

Visscher, J. P. 1928: Nature and extent of fouling of ships bottoms. *Bulletin Bureau of Fisheries 43*: 193–252.

Wiser, S. K.; Allen, R. B.; Clinton, P. W.; Platt, K. H. 1998: Community structure and forest invasion by an exotic herb over 23 years. *Ecology 79(6)*: 2071–2081.

Wonham, M. J.; Carlton, J. T.; Ruiz, G. M.; Smith, L. D. 2000: Fish and ships: relating dispersal frequency to success in biological invasions. *Marine Biology 136*: 1111–1121.

Woods Hole Oceanographic Institution 1952: Marine fouling and its prevention. Annapolis, Maryland, United States Naval Institute. Pp. 1–388.